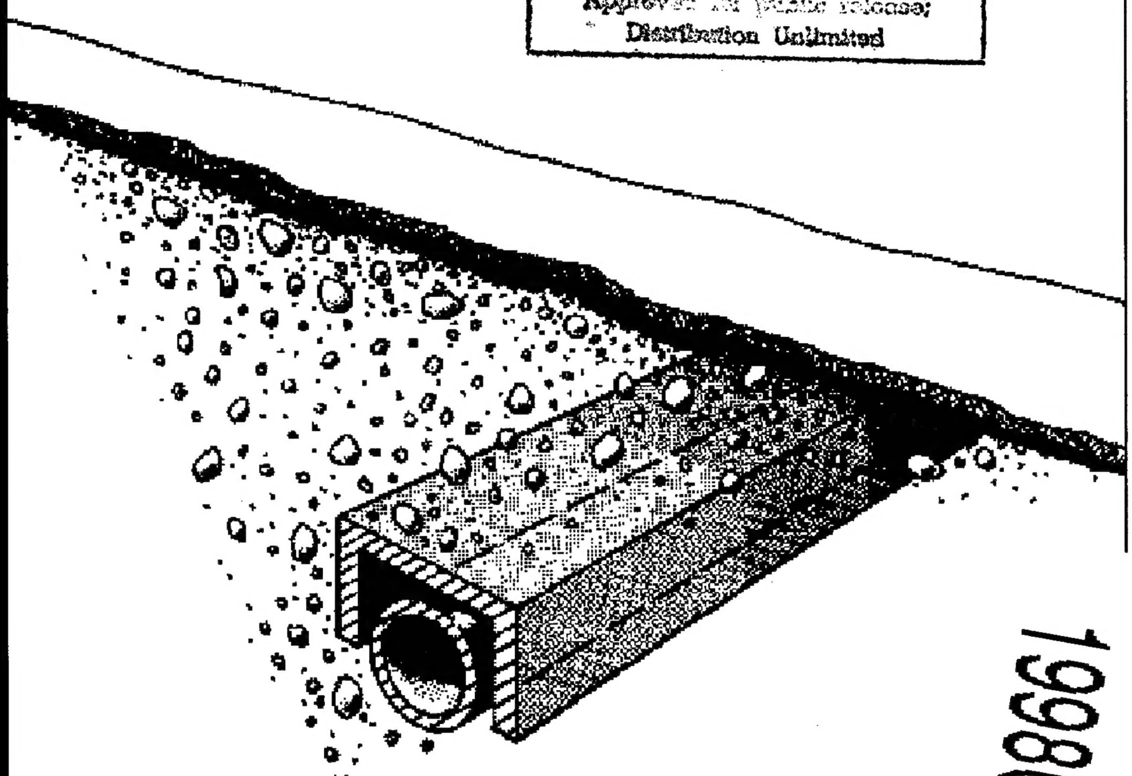
CRREL REPORT 98-4

Frost-Shielding Methodology and Demonstration for Shallow Burial of Water and Sewer Utility Lines

Barry A. Coutermarsh and David L. Carbee

June 1998



Abstract: Burying utility lines below the maximum frost penetration depth can be expensive when difficult digging conditions are encountered or where existing obstacles make the desired depth expensive to achieve. Protecting the pipeline from freezing by adding an insulation shield would allow a shallow burial option. This can reduce excavation costs or avoid the relocation costs of moving the pipeline to an unobstructed location. A finite-element program was developed to model various subterranean heat-flow situations. It was used to design frost shields for a water line in northern New Hampshire through a 4-year Construction Productivity Advancement Research (CPAR) project with the City of Berlin Water Works, the United States Army Cold Regions Research and Engineering Laboratory (CRREL), and the Owens–Corning Specialty and Foam Products Division as partners. Test sites utilizing shielded pipes were constructed, and simple techniques were explored to expedite the installation of the frost shields. Temperatures at the test sites were recorded both to verify the numerical model and to monitor the shield performance. Overall, the numerical model was capable of very good temperature predictions and provided valuable guidance for the frost shield design.

The industry partner participant in the CPAR project, Owens–Corning Specialty and Foam Products Division, intends to market the concept of frost shielding water and sewer lines to state, city, county, and municipal agencies responsible for designing and installing such services. This marketing will be supported by design literature, training of in-house engineers and sales personnel, a case study of this CPAR project, and technical support from Owens–Corning.

CRREL Report 98-4

US Army Corps of Engineers®
Cold Regions Research & Engineering Laboratory

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June 1998

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

PREFACE

This report was prepared by Barry A. Coutermarsh, Research Civil Engineer, and David L. Carbee, Engineering Technician, Applied Research Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire.

The frost shielding project described here was performed under the Corps of Engineers, Civil Works, Construction Productivity Advancement Research (CPAR) program. Under this program, the City of Berlin, New Hampshire, Water Works and U.C. Industries, Inc., (now Owens–Corning Specialty and Foam Products Division), a manufacturer of extruded polystyrene insulation, are partners with CRREL.

Technical review of this report was provided by Dr. Paul W. Richmond III, Mechanical Engineer, CRREL, and John F. Budinscak, Specialty and Foam Products Division, Owens-Corning.

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Frost-Shielding Methodology and Demonstration for Shallow Burial of Water and Sewer Utility Lines

BARRY A. COUTERMARSH AND DAVID L. CARBEE

INTRODUCTION

In climates that experience freezing temperatures, water and sewer pipes are normally buried below the depth of maximum frost penetration. In some areas of the country, this design depth can reach 2.5 m (8 ft) (Nayyar 1992). A shallower trench is desirable in many situations. If ledge is present, the cost of blasting and removing it can make the excavation quite expensive. Furthermore, frost penetration is normally deeper in ledge than in other soils, thus exacerbating the situation. If the in-situ material is environmentally sensitive or otherwise difficult or expensive to excavate, a shallower trench could save both time and money. If isolated obstructions or other utilities are encountered during the pipe installation, an elevation change over the obstruction might be desirable.

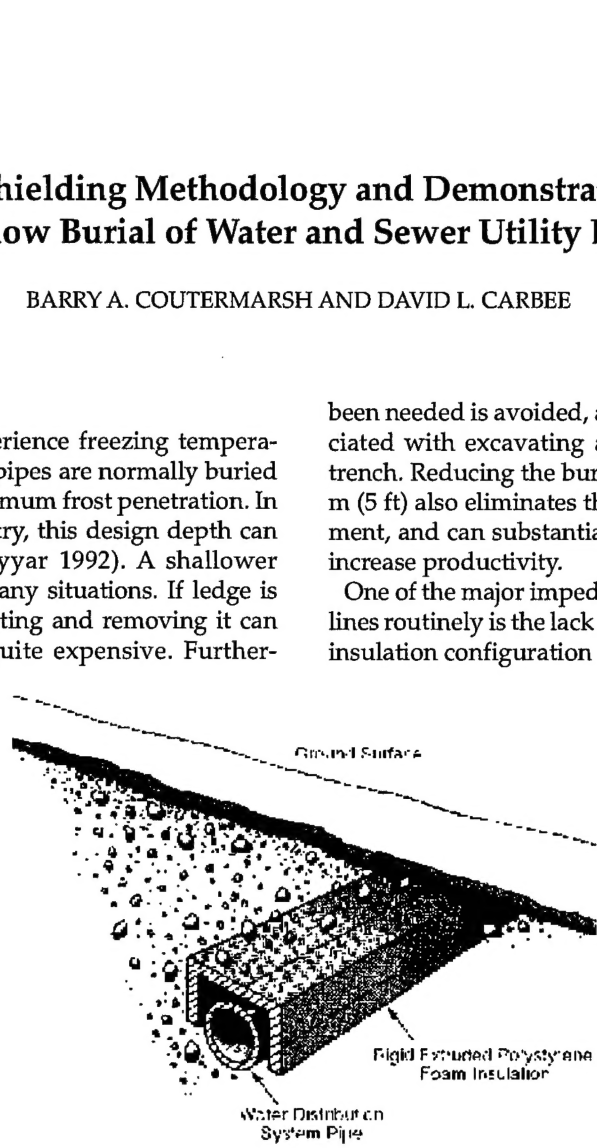


Figure 1. Example of inverted-U frost shield around pipeline.

Frost shielding is the technique of placing insulation in some configuration around a pipe to protect the pipe from freezing, as shown in Figure 1. The increased cost of the insulation and the time to install it are balanced by savings in time and money afforded by decreased burial depth: a smaller amount of material needs to be removed and discarded, the extra backfill that would have been needed is avoided, and time savings are associated with excavating and backfilling a smaller trench. Reducing the burial depth to less than 1.52 m (5 ft) also eliminates the OSHA shoring requirement, and can substantially decrease expense and increase productivity.

One of the major impediments to insulating pipelines routinely is the lack of design guidance for the insulation configuration and thickness. The design of the shield is affected by the variables of climate, burial configuration, soil characteristics, and pipe temperature. The designer must also choose an acceptable "freeze time," i.e., an amount of time before the pipe freezes if there is no flow (and thus no heat) within it. CRREL has developed a finite element (FE) program that allows the designer to assess the impact of each of the variables and see how the changes affect the freeze time. The program models two-dimensional subterranean heat flow, with phase change, and describes the results both numerically and visually using graphs and contour plots. This program allows the designer to create several different shield configurations and assess the thermal performance of each. A cost analysis can then be performed to determine the most efficient shield design to use.

Insulation to protect utility lines has been used in an ad hoc manner throughout the world. The practice was formalized most notably in Norway, where Per Gunderson has been instrumental in this effort by developing nomographs that provide guidance on shield designs. The Norwegians have also collocated sewer, power, and domestic water lines within the shield, providing a heat source that allows even shallower burial depths (Gunderson 1975, 1989). Gunderson's work encouraged CRREL to pursue the shielding research, with the added flexibility that the FE program gives in determining shield configurations where soil parameters, climate, and pipe designs can be varied.

The project ran from 1993 to 1997 with two shielded 0.203-m (8-in.) pipelines constructed by the City of Berlin Water Works. The shields were designed by CRREL, with engineering consulting and insulation provided by Owens–Corning. CRREL also monitored the temperatures in and around the shields and performed data reductions and comparisons. In addition to the shielded designs, an unshielded pipeline was also monitored as a baseline comparison. The first year's shield design and installation are detailed in Coutermarsh (1997), which provides details on the construction and installation techniques used as well as a first-year assessment of the shield temperatures. This report reiterates some of the important design and construction details, but the reader is urged to refer to Coutermarsh (1997) for a more detailed look. This report focuses on the steps taken to design the shield and performance comparisons between the design and actual insitu temperatures.

Objective

The objective of this project is to evaluate, through field studies and demonstrations, the effectiveness and design of insulation shields to prevent the freezing of water and sewer utility lines buried in the frost penetration zone. Specific goals include

- Evaluating the effectiveness of a finite element heat transfer program developed to assess various insulation and utility line configurations subjected to any given environmental conditions.
- Evaluating the effectiveness of insulation shielding schemes.
- Evaluating and developing guidance on construction techniques for installing frost shields.

Approach

The project was divided into three phases. In the first phase, an insulated shield design was developed, through numerical modeling, for a water line buried in ledge in Berlin, New Hampshire. Phase two consisted of constructing, monitoring, and evaluating the design developed in phase one. In this phase as well, a second design was developed, based upon the performance of the first shield, and installed at another test site in Berlin. Phase three is the technology transfer and commercialization of the results.

Designing a shield

A brief overview of designing a shield is presented below. Each step is looked at in more detail in the context of this study later in the report.

The general procedure used in designing a shield is first to decide the depth that is desired for the pipe. This is frequently dictated by physical constraints present along the pipeline path, i.e., the presence of ledge or other obstructions, or by cost considerations. Then one must decide what type of shield configuration is feasible, based upon the size of the pipe, available insulating materials, and site constraints. Here the constraints may be the presence of other utilities nearby, difficult digging conditions, or right-of-way considerations. In addition, since the shield design may allow insulation to be laid near the surface of the roadway, the type and weight of traffic on the road may necessitate a loading calculation to ensure axial loads are properly distributed so the bearing capacity of the insulation is not exceeded. Under some conditions, insulation beneath a roadway can cause differential icing on the surface. We placed the insulation no closer than 0.508 m (20 in.) below the surface to minimize the effect of differential icing on the roadway.

The physical configuration of the trial shield and pipe are then duplicated in the FE mesh, and a numerical simulation is performed in two steps. First, the simulation is run with the influence of the surface temperature and pipe temperature for the climate where the pipe is located. This initial run sets the correct temperatures throughout the mesh. In the final step, the water temperature is turned off at a time the designer chooses, which simulates turning the water flow off in the pipe. The simulation is then run to see if and when the pipe temperature reaches 0°C (32°F). The results of the simulation will indicate whether the design is adequate. If it is not, then adjustments are made to the shield, e.g., add more insulation, change the

configuration around the pipe, or change the burial depth, until the results are satisfactory. Once a successful shield design is found, then an economic analysis can be performed to see if the added cost of the shield is less than the cost of burying the pipe deeper.

NUMERICAL MODEL

In this project, a CRREL-developed finite element program with a phase-change algorithm was used to design the frost shield. It should be emphasized that any FE program with an accurate phase-change capability should be adequate for designing.

The designer uses the dimensions of the pipe, shield, and surrounding soils to create an FE mesh that models the physical configuration of the desired shield and pipe. This mesh consists of a series of triangular elements arranged in zones that accurately represent the design being studied. The density of the element spacing is dependent upon the thermal gradients expected in the zone. There is a nodal point at every line intersection in the mesh. It is at these nodal points where the temperatures are calculated during the simulations. A vertical line of symmetry is used through the center of the design to reduce the number of elements and thus modeling time and resources. Figure 2 shows a portion of a mesh used to model an inverted-U insulation shield around a pipe. In the figure, the darker area is the insulation. Further information on FE modeling can be found in any textbook on the subject (see, for example, Segerlind 1984).

The thermal and physical properties of each material in the mesh are input to the program via a materials file. The properties needed in the program for each material are: thermal conductivity, density, specific heat, latent heat, and phase-change temperature (if required).

Along with the physical configuration and material properties, the mesh needs boundary conditions at the edges. The left and right sides of the mesh are set as zero heat flux boundaries. This in essence defines anything beyond the edges as being thermally identical to the thermal conditions present at the edges. This is certainly true at the line of symmetry, and the mesh is extended out to 4.5 m (14.8 ft) wide to ensure the outside boundary meets this criterion. The mesh extends to a depth of 10 m (32.8 ft), which is a reasonable approximation of the depth of zero annual temperature amplitude, i.e., the temperature at that depth does not vary with the surface temperatures. The bottom boundary condition is set as the average geothermal heat flux of 0.063 W/m^2 (Lunardini 1981). This is theoretically the amount of heat flowing up from the center of the earth. The top boundary condition is the surface temperature present at the location being modeled. In a design situation, this would probably be the coldest expected surface temperature at the pipeline location.

A distinction should be made between air temperatures and surface temperatures. Air temperatures on average tend to be cooler than surface temperatures, at least in New England. The designer could choose to use air temperatures for design considerations, or these air temperatures can be adjusted to surface temperatures through the use of *n* factors that adjust for the effect that surface material, radiation, and other heat transfer modes have upon the surface temperature (Lunardini 1981).

In addition to the edge boundary conditions, it is necessary to add a boundary condition to define the heat coming into the shield from water flowing within the pipe. In the modeling, this temperature is used during the first step to compute the correct mesh temperatures under the influence of all the boundary conditions. This step is necessary to correct any temperature errors caused by start-up error. Initially, every nodal point in the mesh must have a temperature assigned to it, and frequently a constant temperature is used throughout. This would not be the case in reality, since the nodes near the surface or near the pipe would be influenced more by the

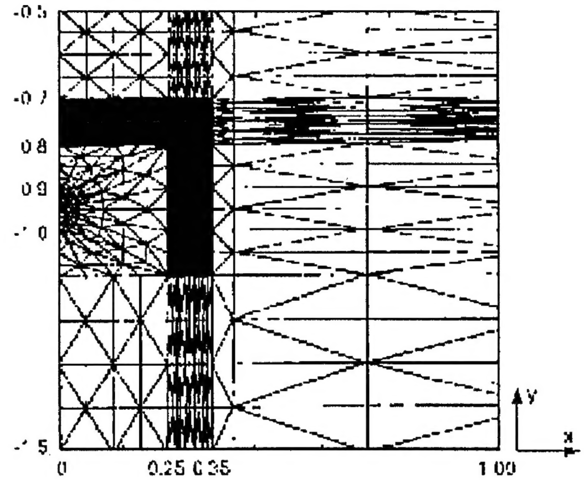


Figure 2. Finite-element mesh showing mesh refinement necessary for insulation and pipe.

nearby boundary condition temperatures than would the nodes farther away. By performing several years of simulation, the FE program internally corrects this start-up error.

Once the start-up error is removed, the second step is to check the length of time it takes for the pipe to freeze. The temperature boundary condition at the pipe is removed (simulating no water flow), and the simulation is run until either the frost penetration reaches its maximum or the zero-degree temperatures touch the pipe. If the 0°C isotherm reaches the pipe, the amount of time that it took to do so can be calculated and compared to the desired time of protection. If the outcome is not satisfactory, a different design can be tried, using the first previous results to guide the design. The desired time of protection is determined by the design engineer for the location and level of acceptable risk.

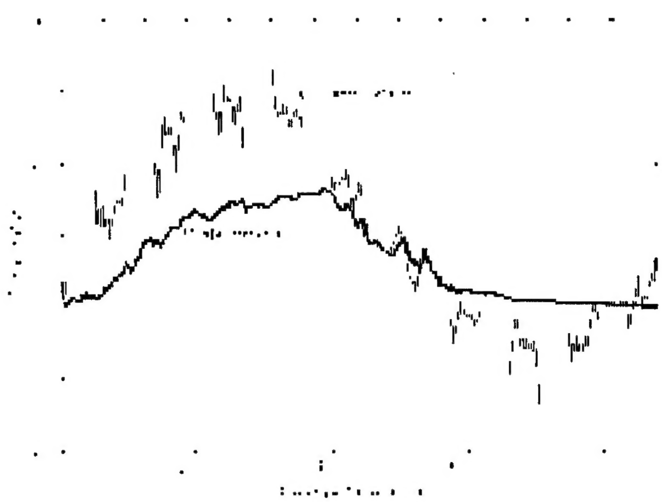


Figure 3. Temperatures recorded at surface of Labossiere Street and water temperature in pipe below. Note lag between time of peak surface temperature and peak pipe temperature.

BERLIN FIELD STUDIES

Shield design and thermocouple layout

General design considerations

The surface material above the pipeline can have a noticeable impact upon surface temperatures. This material should be accounted for (e.g., by using an *n* factor) when designing from air temperatures. The coldest surface temperatures expected should probably be used in the design, but that is a decision the designer will have to make. All of the CPAR test pipelines were installed in the street right-of-way and have asphalt as a top surface material, which is plowed in the winter. They therefore did not get any benefit from snow or grass cover, which can provide a warmer surface than a plowed road does.

The water temperature in the pipe can have a large impact upon the success of a design in that a relatively warm water supply can provide energy to the soil within the shield. Accurate water temperatures are therefore important to the shield design. A phenomenon noticed in the Berlin studies was a phase shift of the water temperatures in the pipe compared with the surface temperatures. Figure 3 shows this shift from the Labossiere Street data. It is evident that in the summer the water in the pipe reaches its peak temperature about 600 to 700 hours after the surface temperature peak. A similar or longer lag is evident during the cooling season. This shift is probably caused by a combination of factors. The water temperature at the source does not react as quickly to air temperature changes as the surface does, due to its mass and specific heat. In addition, if the water flow rate is low and it stays in the pipe for an appreciable amount of time, it will tend to equilibrate with the temperature of the soil at the pipe burial depth. This temperature will be out of phase with the surface temperature because of the insulating effect of the soil above. If the water temperatures within the pipe are very cold, the timing of this shift can have an effect upon the time to freeze.

Labossiere Street

Two independent insulated pipe test sections were installed in the field tests in Berlin, N.H. The first design was built in the summer of 1994 on Labossiere Street in an area where ledge was present to the surface along most of the pipeline. This was the first and purposely conservative shield design until some experience and data were acquired to verify the model simulation. The background of this design is explained fully in Coutermarsh (1997), with a synopsis below.

The basic physical configuration of the pipeline and shield along with the thermocouple (TC) monitoring locations is shown in Figure 4. The pipe is a 0.2033-m- (8-in.-) diameter ductile iron pipe about 123 m (405 ft) long on a dead-end water line with low flow, and it is buried about 1.5 m (5 ft) deep. A 0.15-m- (6-in.-) thick, inverted-U shield was placed over the pipe with the bottom of the legs at or

slightly below the bottom of the pipe. The shield was 1.2 m (4 ft) wide and 0.76 m (2.5 ft) high and was built up using 0.051-m- (2-in.-) thick, 1.22- × 2.44-m (4- × 8-ft) SSE boards of SP-Formular® 250 extruded polystyrene foam insulation. The trench was blasted in ledge slightly wider than the shield and was backfilled with sand.

In these first design runs, the surface boundary condition was an equation regressed to the coldest *air* temperatures that had been found in 66 years of records (Fig. 5). It was felt this gave a conservative (i.e., somewhat colder than expected) boundary condition. The failure criterion used was that the pipe temperature was not to drop to 0°C. This criterion was later considered to be too severe, and it was modified on the second design, explained later. The design shown in Figure 4 gave results that met this criterion. More details on this design can be found in Coutermarsh (1997).

2nd Avenue

In the summer of 1995, a thermocouple (TC)

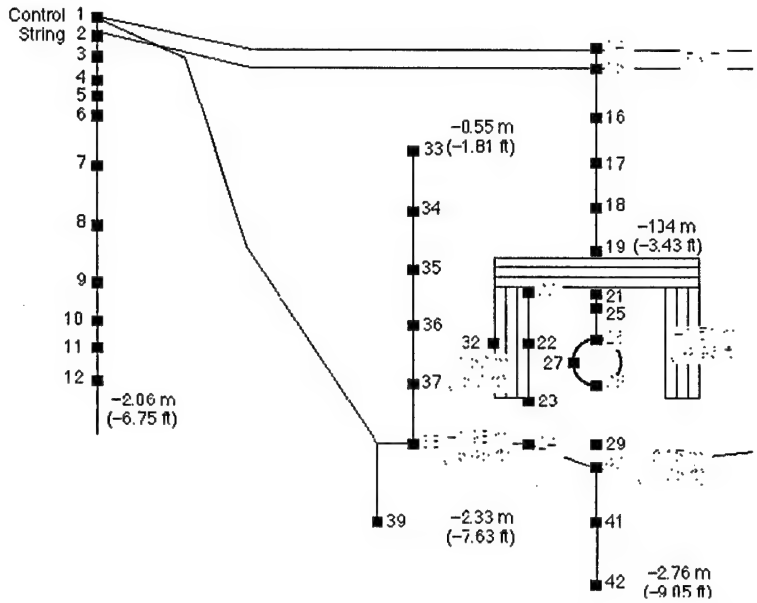


Figure 4. Physical configuration of Labossiere Street pipe and shield. Thermocouple locations are indicated by small squares.

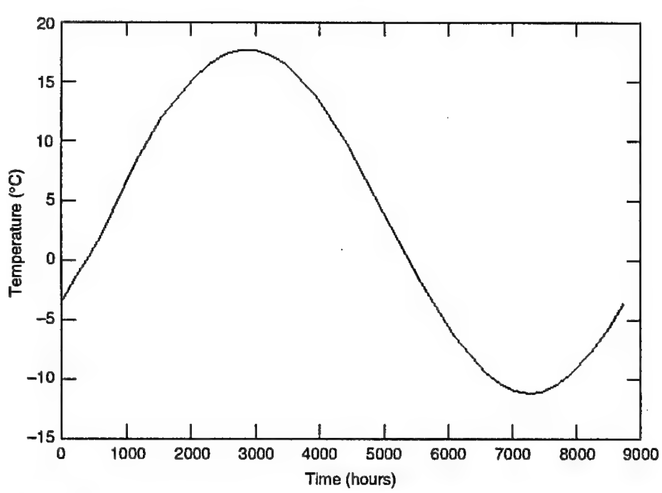


Figure 5. Average daily coldest temperatures regressed to sine curve and used as design surface temperature during shield design FE runs.

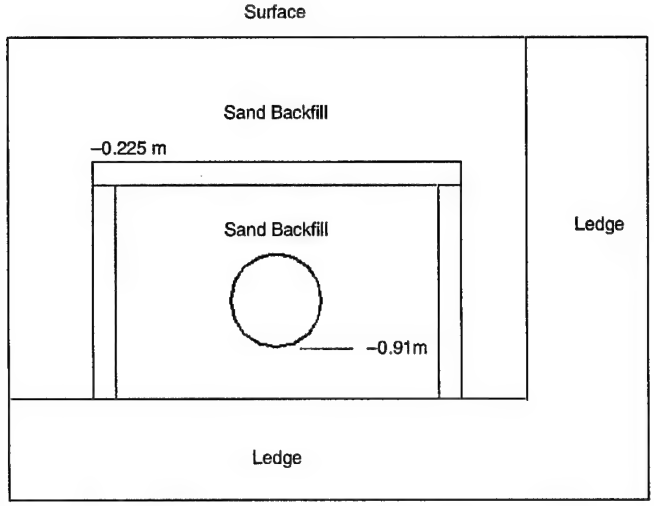


Figure 6. Initial design configuration used at Wentworth Street. Bottom of pipe was placed at 0.91 m (3 ft) in this design. Top of insulation was 0.225 m (9 in.) below surface.

string was installed above an uninsulated 0.2033-m (8-in.) pipe on 2nd Avenue, buried about 2.13 m (7 ft) deep, to record temperatures from the surface down to the pipe. An immersion TC and a flow meter were also installed in the pipe to record water temperatures and flow rate. The uninsulated water line on 2nd Avenue was part of a larger loop and thus gave water temperatures in a part of the distribution system that would have a higher water flow than the dead-end line on Labossiere. This would help assess the differences in water temperature for two different locations in the distribution system and determine baseline data around an uninsulated pipe. The data also served as a backup for and a comparison with the surface and air temperatures gathered on Labossiere Street.

Wentworth Street

The second insulated pipe section was constructed on Wentworth Street. Based upon the good agreement between the numerical model and the data gathered from Labossiere Street, the failure criterion for the shield design was changed to allow the pipe to reach 0°C and to assess the length of time it took to do so. Warmer temperatures were expected in the pipe at Wentworth from information provided by the water works regarding the source of the water. It was also expected, from test explorations at the site, that the pipe would be resting on ledge rather than buried directly in it. Thermally, this is a much better situation than at Labossiere Street.

In the initial design investigations for Wentworth Street, a pipe depth of 0.91 m (3 ft) surrounded by ledge to the surface was assumed. This physical configuration, shown in Figure 6, gave a conservative design arrangement, i.e., the highest expected thermal conductivity, to verify the system performance in a thermally demanding shallow burial installation.

The design thermal boundary conditions used the cold design year surface temperatures at the top of the mesh along with the measured 2nd Avenue water temperatures, with 1.5°C added to them, to simulate slightly warmer water than at Labossiere. The geothermal heat flux boundary condition was at the bottom of the mesh at 10-m (32.8-ft) depth in all the runs.

To assess the time to freeze, the water flow was shut off (the temperature boundary condition at the pipe was removed) at two different times corresponding to the time of minimum top surface temperature (MTT) and the time of minimum water temperature (MWT), and the time until the 0°C isotherm touched the pipe was recorded. The design runs showed that if the water was shut off at MTT, it was 290 hours before the 0°C isotherm arrived at the pipe, and at MWT, 27 hours passed. The maximum frost penetration for this simulation was approximately 2.1 m (6.9 ft).

This design was acceptable to provide freeze protection to the pipe, but there was some concern about possible surface icing on the street above with the insulation so close to the surface (0.2246 m [8.8 in.] in this case). The issue of sur-

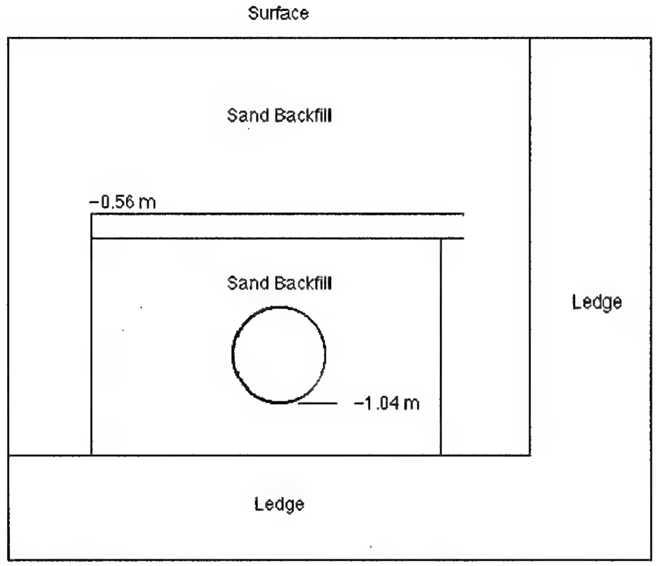


Figure 7. Final design configuration used at Wentworth Street. Here bottom of pipe is 1.04 m (3.4 ft) deep and top insulation board is 0.56 m (1.8 ft) below surface.

face icing is discussed in the *Conclusions* section. A depth of at least 0.508 m (20 in.) below the surface for the insulation was acceptable to all parties, and further design runs were performed. The new design configuration was as shown in Figure 7. Here the pipe depth is 1.04 m (3.4 ft) with a 0.1016-m- (4-in.-) thick shield. This put the top insulation board 0.56 m (1.8 ft) below the surface.

The time-to-freeze assessment showed times of over 200 hr (the simulation was ended before the pipe reached 0°) from MTT and 35 hr from MWT. The MWT time was an increase of 8 hr from the 0.91-m (3-ft) pipe depth tried earlier.

It was felt that the worst-case physical scenario on Wentworth Street would be as modeled above, i.e., if there was actually ledge to the surface when it was expected to be down at about the 0.91-m (3-ft) depth. On this basis, it was decided to install a 0.1016-m- (4-in.-) thick shield around the pipe.

Shield installation

Wentworth Street runs uphill at a slope of about 6% between Cascade Street and Williams Street in Berlin, N.H. The 0.2032-m- (8-in.-) diameter ductile iron pipe was buried at depths to about 1.33 m (4.4 ft) on top of some existing ledge. The parent soil down to the ledge is a gravelly sand with an appreciable amount of fines. Since the actual ledge was deeper than had been anticipated during the modeling, this was a more conservative design than was probably necessary. An inverted-U shield was again placed over the pipe, this time only 0.1016 m (4 in.) thick. The total shield width was 1.2 m (4 ft), and the total height was 0.71 m (28 in.). The shield was also constructed using two layers of 0.051-m- (2-in.-) thick, 1.22- × 2.44-m (4- × 8-ft) SSE boards of SP-Formular® 250 extruded polystyrene foam insulation. As at Labossiere, the trench excavation was backfilled with sand. Figure 8 shows the general shield and pipe configuration along with the TC locations for monitoring the temperatures.

The new pipe was tied into an existing line at Cascade Street, where there were several interfering sewer lines and there was ledge near the level where the pipe had to be laid to clear them. Because of this interference, the water works decided to lay a few sections of pipe before starting a complete shield. Insulation boards were laid horizontally over this first section, with about 56.1 m (184 ft) of the 86.5-m (284-ft) pipeline getting a full inverted-U shield.

The pipe and shield installation went very similar to the Labossiere Street installation described in Coutermarsh (1997), except most of the digging was in the parent material rather than ledge. The excavation was taken down to about the level of the existing ledge, and approximately 0.1524 m (6 in.) of medium clean sand was put in the bottom for a pipe bed, with the pipe and shield constructed on this. Sand was used as a backfill around and in the shield. Wooden jigs were again used on both the top and bottom of the insulation

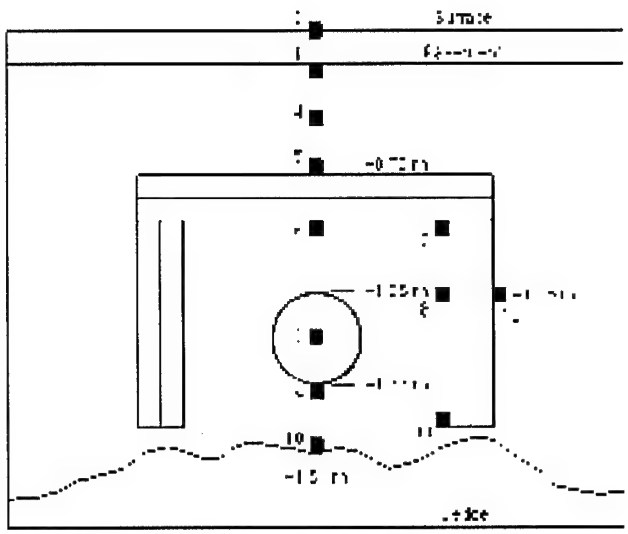


Figure 8. As-built configuration on Wentworth Street showing thermocouple locations as small squares. Bottom of pipe at test site was about 1.33 m (4.4 ft) deep with top insulation board about 0.7 m (2.3 ft) below surface.

boards to hold them in place during construction (Fig. 9), and all the shield joints were staggered (Fig. 10) to prevent thermal short circuits. The sand backfill was added evenly to the inside and outside of the shield to prevent the soil pressure from collapsing the walls, and it was compacted with a vibratory compactor. After the sand was up to the level of the top of the shield side walls and had been compacted, the excess was screed off and the top horizontal boards were laid (Fig. 11). Care was taken to position the boards so there were no gaps between them and the vertical side boards. These top boards were also staggered to prevent thermal short circuits.

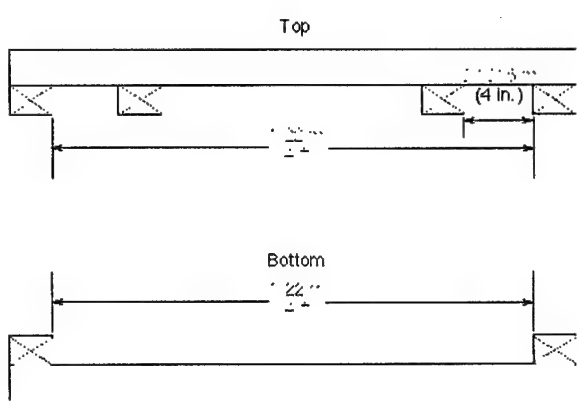


Figure 9. Jigs made from 2 × 4 lumber to hold insulation during installation.

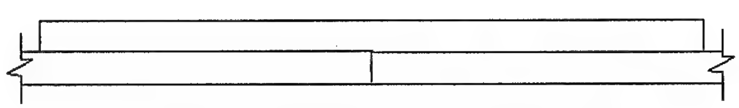


Figure 10. Staggered insulation board joints.

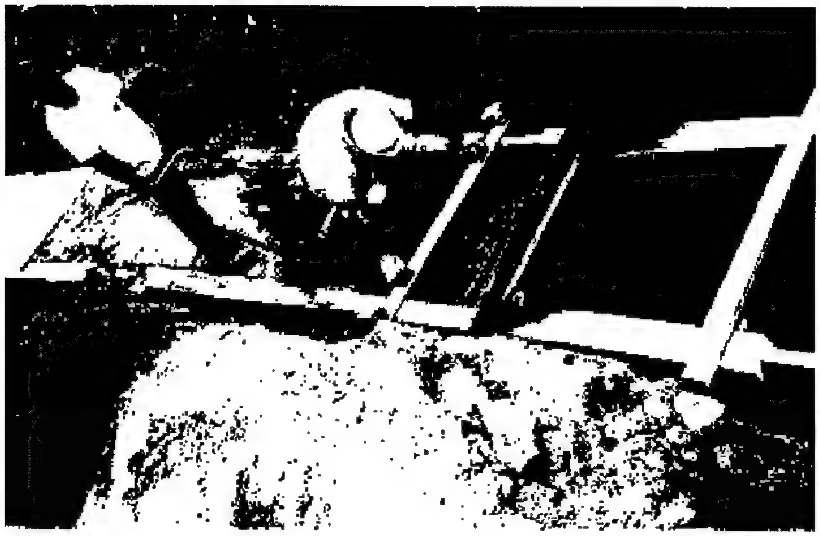


Figure 11. Insulation shield side boards in place with sand backfill being leveled off and compacted. Bottom and top wooden jigs hold sides in place during construction. Bottom remain in place and top ones are removed before top insulation is placed.

Instrumentation

There was one main TC location about midway along the shielded section of pipe. Ledge was located here about 1.5 m (4.95 ft) deep. The bottom of the pipe was about 1.3 m (4.3 ft) deep. Several TCs were located around and in the shield, with several positioned vertically above the shield extending to the surface. An immersion TC was placed in the pipe to record water temperatures. (Thermocouple locations are shown in Figure 8.) Two TCs were placed at the beginning of the pipeline: one under the horizontal insulation and one above. In addition to the buried TCs, one was also installed beneath the datalogger enclosure box to record air temperatures at the site.

MODEL VERIFICATION

Boundary conditions

The temperatures recorded at the three sites were used to provide boundary conditions to the FE simulations to verify the agreement between actual and predicted temperatures. The preliminary design mesh was changed to reflect the actual physical configuration present after construction. The recorded surface temperatures at the sites were used as the top boundary conditions, with the immersion TC data providing the pipe boundary condition.

Material properties

Moisture content is probably the most important property to be considered in the thermal modeling of in-situ material, due to its effect upon the thermal conductivity of the material as well as the retarding effect the latent heat of water has on the progression of the freeze front. Furthermore, the frozen and unfrozen thermal conductivity of soil can vary according to moisture content density and soil type. Figure 12 is a plot taken from data by Kersten (1949) showing the difference in frozen and unfrozen thermal conductivity of an 1800 kg/m^3 sandy soil with varying moisture content. This would be similar to the backfill sand used around the pipes. It can be seen that at moisture contents below about 9%, the frozen conductivity is lower than the unfrozen conductivity even though the thermal conductivity of ice is about $3^1/_2$ times greater than water. Balanced against the greater thermal conductivity is the retarding effect the latent heat of the moisture has upon frost penetration.

The materials present at the Labossiere Street site were the backfill sand and ledge. The ledge was at first modeled as a continuous mass of solid rock that had a relatively high thermal conductivity. During construction, it was evident that much of the ledge was fractured, and water was seen to come out of the drill holes used to insert charges for the blasting. These seams of water would greatly

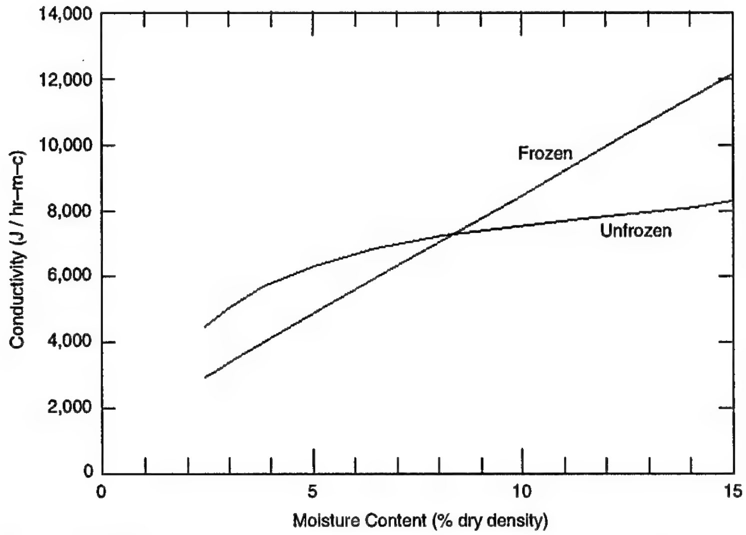


Figure 12. Frozen and unfrozen thermal conductivity, plotted against moisture content, of 1800 kg/m³ sandy soil. (From Kersten 1949.)

Table 1. Uncorrected and corrected Labossiere ledge material properties.

	Conductivity (J/hr m °C)	*Density (kg/m³)*	*Specific heat (J/kg °C)*
Uncorrected ledge	9242	2700	879
Corrected ledge	6208	2700	1375

influence the thermal conductivity of the material, as opposed to assuming only rock. After the first year's assessment of the results, it was evident that the ledge conductivity in the model was too high to represent in-situ conditions. The conductivity was subsequently altered by determining an effective thermal conductivity of the ledge and water together by using simple Wiener bounds (Farouki 1981) based upon estimates of the volumetric moisture content.

This procedure works by first assuming the water and ledge occur as two separate blocks in a parallel arrangement with the heat flow. The effective thermal conductivity for this arrangement is the upper limit of the conductivity and is given by

$$k_e = x_s k_s + x_f k_f.$$

The subscripts s and f refer to solid and fluid, respectively, and x is the volume of the material per total unit volume. The lower limit of the effective conductivity is given by arranging the fluid and solid portions in series with the heat flow:

$$1/k_e = x_s / k_s + x_f / k_f.$$

This procedure produces upper and lower bounds for the conductivity based upon the position of the moisture relative to the heat flow. The values used for the uncorrected and corrected Labossiere ledge material are shown in Table 1.

Sand backfill has a relatively small (2% to 8% by weight) moisture content that varies depending upon the type and quality of the material.

The 2nd Avenue and Wentworth Street sites had parent material consisting of gravelly sand with an appreciable amount of fines, medium clean sand backfill, and ledge. The ledge at both of these sites was beneath the pipe and therefore did not contribute to a faster and deeper freeze-front progression down to the pipe. The parent material outside of the trench was modeled as a sand with low moisture content to obtain a conservative (deeper) freeze-front progression than would be present if it were a soil with a much higher moisture content. Table 2 shows the thermal properties used in the modeling.

Table 2. Material properties used in numerical simulations.

	Conductivity (J/hr m °C)	*Density (kg/m³)*	*Specific heat (J/kg °C)*	*Latent heat (J/m³)*
Sand				
Frozen	5616	1836	784.8	
Unfrozen	6228	1836	940.32	45.3×10^6
Water				
Frozen	7984.8	917.0	2096.2	
Unfrozen	2170.8	998.2	4183.92	334×10^6
Extruded polystyrene	93.46	28.84	1339.8	
'95–'96 ledge	9242	2700	879	
Ledge	6208	2700	1375	

LABOSSIERE STREET RESULTS

The three winters when this project was running were not relatively cold ones. However, whatever the temperatures, if the numerical model is valid, it should be able to mimic accurately what was recorded. Figure 13 shows the maximum frost penetration measured at the control string inserted in ledge on Labossiere Street, compared with the simulated frost penetration. The winter of 1994–1995 has two entries. The first shows the maximum frost penetration up to a prolonged warming spell (with near-record warm temperatures in January) of 1.04 m (3.4 ft) with the simulation being 1.08 m (3.5 ft). The second maximum penetration happened after this warm period, in early March, and was 1.06 m (3.5 ft); the numerical was 0.94 m (3.1 ft).

The 1995–1996 entries show the frost penetration simulation using the corrected thermal conductivity for the ledge and the uncorrected high thermal conductivity (k). This shows the dramatic difference between assuming pure ledge conductivity and adopting a more realistic conductivity. The measured maximum frost depth was 1.32 m (4.3 ft). The simulation using the corrected conductivity gave a depth of 1.4 m (4.6 ft) and the uncorrected conductivity resulted in a depth of 2 m (6.6 ft), 43% higher than the uncorrected conductivity. This underscores the importance of having accurate physical properties for the materials on site.

The 1996–1997 maximum frost penetration came around mid-February at 1.14 m (3.7 ft). The predicted depth was 1.1 m (3.6 ft).

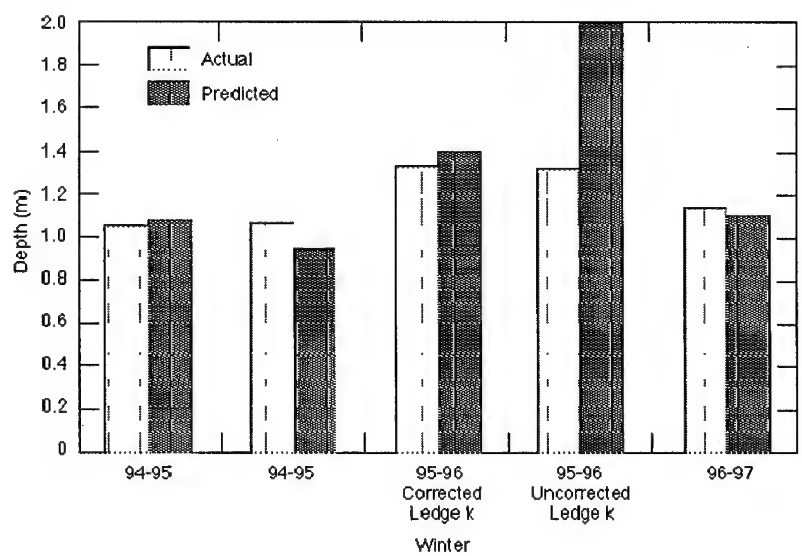
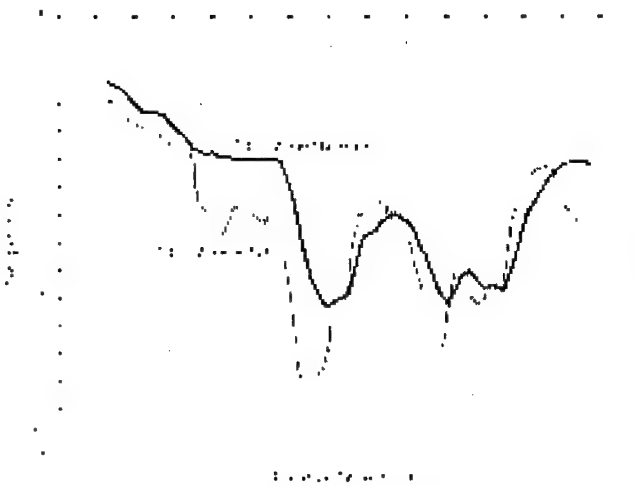
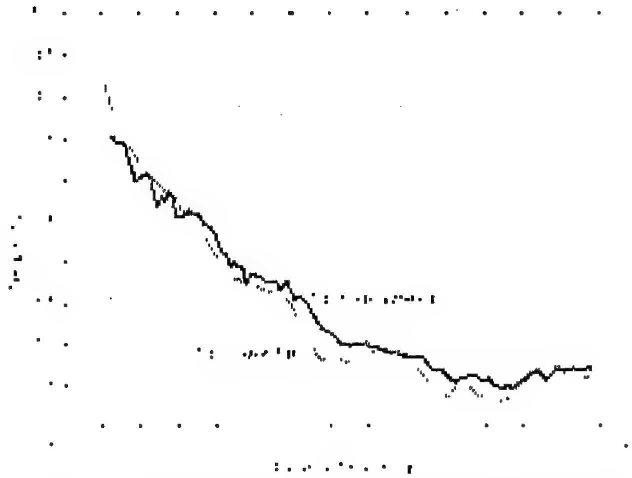


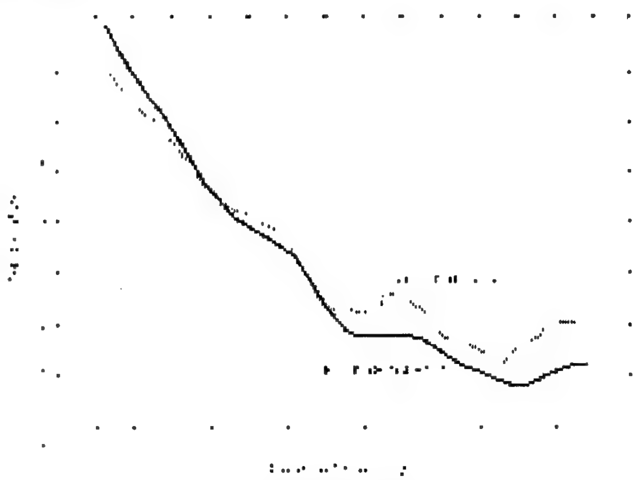
Figure 13. Actual and predicted frost penetration data. Winter of 1994–1995 has two entries because of long warming spell in middle of winter. Effects of uncorrected and corrected ledge thermal conductivity values are shown for winter of 1995–1996.



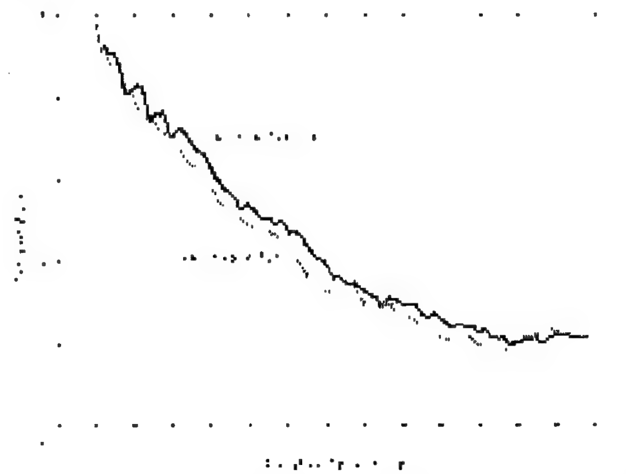
a. Top center insulation board, outside shield. Thermocouple 19 in Figure 4.



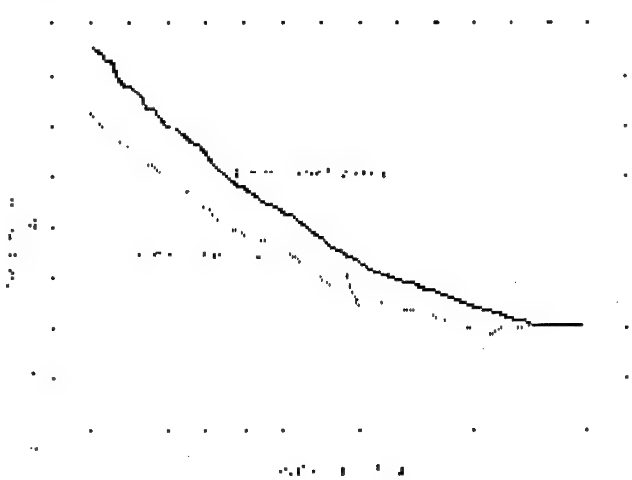
b. Thermocouple 21 in Figure 4. Top center insulation board, inside shield.



c. Thermocouple 32 in Figure 4. Middle of side board, outside shield.

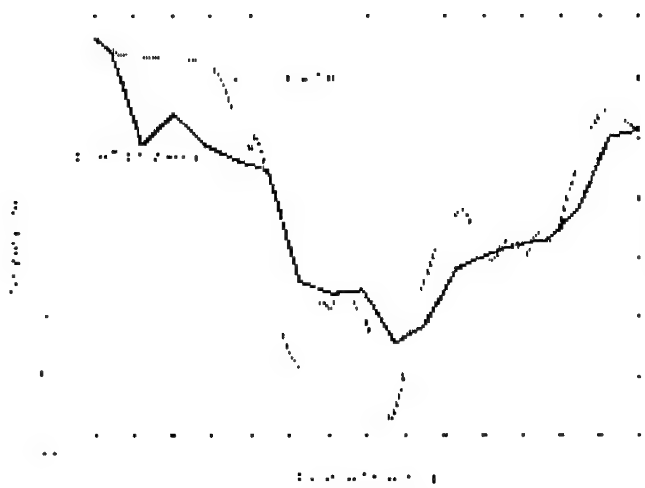


d. Thermocouple 22 in Figure 4. Middle of side board, inside shield.

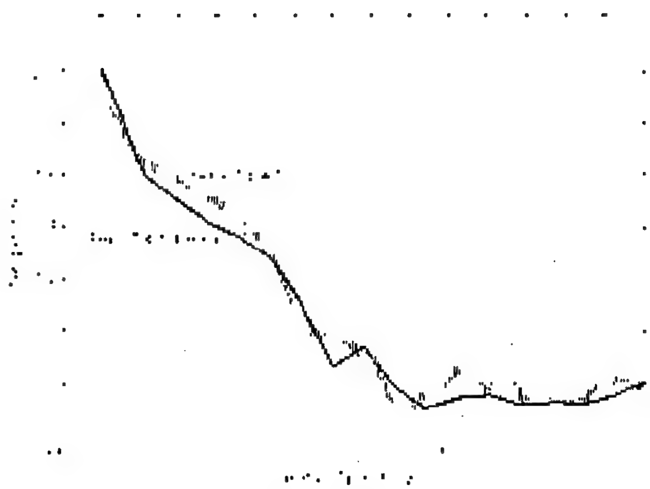


e. Thermocouple 23 in Figure 4. Bottom corner, inside shield.

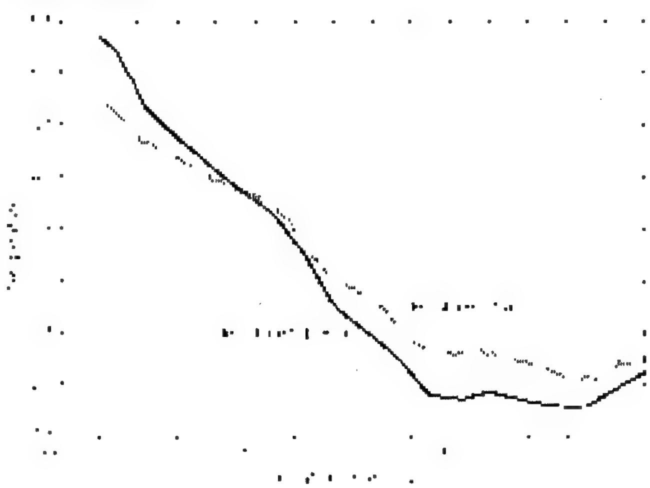
Figure 14. Actual vs. numerically predicted temperature/time graphs for Labossiere Street during winter 1995–1996. Temperatures are compared at thermocouple location listed for each figure.



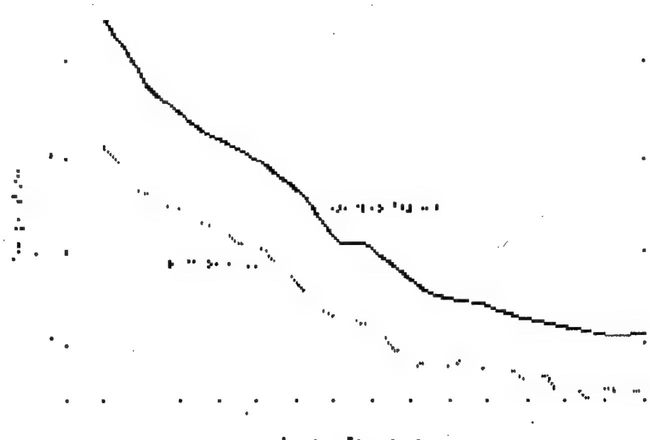
a. Thermocouple 19 in Figure 4. Top center insulation board, outside shield.



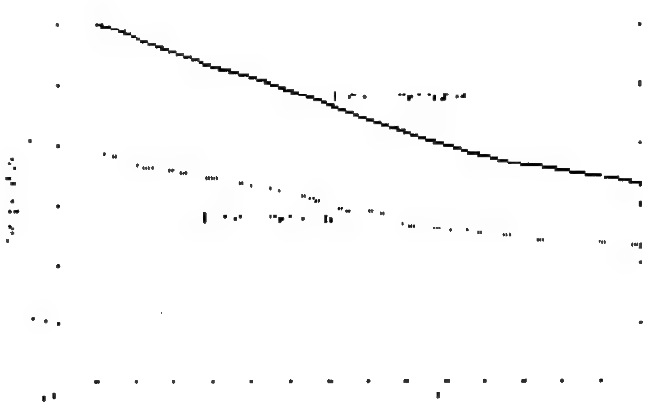
b. Thermocouple 21 in Figure 4. Top center insulation board, inside shield.



c. Thermocouple 32 in Figure 4. Middle of side board, outside shield.



d. Thermocouple 22 in Figure 4. Middle of side board, inside shield.



e. Thermocouple 23 in Figure 4. Bottom corner, inside shield.

Figure 15. Actual vs. numerically predicted temperature/time graphs for Labossiere Street during winter 1996–1997.

As is evident, there is good agreement between the numerical simulations and the actual temperatures recorded in the ledge material.

In addition to maximum frost penetration, actual temperatures at several points around the shield were compared with the simulation during the coldest time of the year. The thermocouples used in the verification as shown in Figure 4 are the top center inside (TC 19) and outside (TC 21), the side inside (TC 22) and outside (TC 32), and the bottom inside corner (TC 23). Figure 14 shows the comparison between the actual temperatures and the simulation temperatures for winter 1995–1996, and Figure 15 shows the comparisons for winter 1996–1997. The numerical simulation generally produces very good agreement with the recorded temperatures for both years. The numerical temperature at the outside middle of the top of the shield shows some discrepancy at the coldest dips in the temperature–time record during both years. In the winter of 1995–1996, this amounted to about 2.5°C at the first cold dip around 7200 hr but decreased to about 1.5°C by 8000 hr. It appears that the numerical simulation remained at the phase-change temperature longer than the actual temperatures did between 6100 hr and 7100 hr and thus the simulation did not reach the coldest temperatures at 7200 hr. In the 1996–1997 simulation, the numerical dipped below the phase-change temperature before the actual temperatures, but the magnitude of the discrepancy at the coldest time is only about 1°C.

This discrepancy in the top center outside thermocouple (TC 21) was also noticed in the Wentworth Street data. One possibility for this difference might be that the numerical simulation assumes the moisture to be spread evenly throughout the material when in the actual situation moisture migrates to the freezing front. The horizontal insulation boards block this natural moisture migration, so the area right above the shield would not be receiving moisture from below. This area would therefore be drier than what the numerical model assumes, which may result in lower temperatures in this area than the numerical prediction would give.

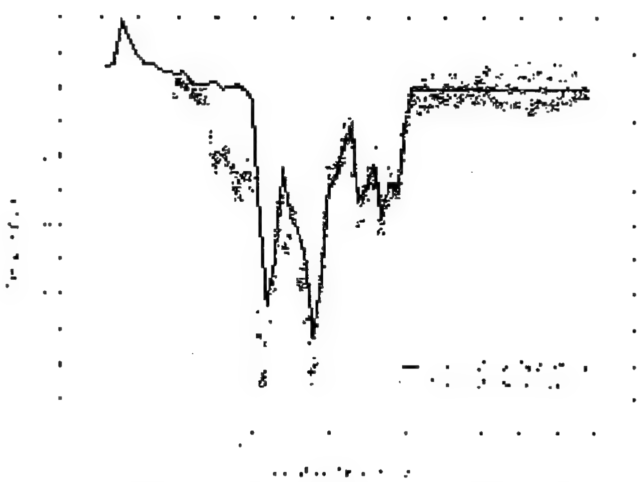
It has also been noticed that a much smaller time step in the FE program can have a substantial impact upon the delineation of the phase front. A small time step, however, will substantially increase the numerical simulation run time to obtain an accuracy that is not always necessary.

The simulation shows excellent agreement at the other positions in the shield. The worst case is the 1996–1997 winter at the bottom corner. Here the difference between actual and numerical starts out at about 2°C and converges to about 1.25°C. The bottom corner agreement can be dramatically affected by the close proximity of the ledge. In the numerical simulation, the ledge was modeled as smooth, uniform, and a constant distance from the shield, at the bottom surface of the trench. Obviously this is not the case in the actual construction, and this could account for some temperature variations at the corner.

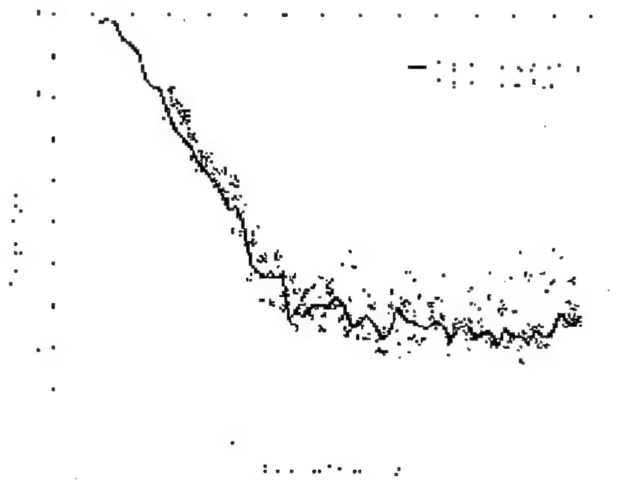
WENTWORTH STREET RESULTS

The Wentworth Street site does not have a control string to measure the frost penetration, so for the verification only temperatures in several locations around the shield were compared. Thermocouples in the same relative location as at the Labossiere site were used and they are, as shown in Figure 8, top center inside and outside TCs 6 and 5, side inside and outside TCs 8 and 12 and the inside bottom corner TC 11. Figure 16 shows the agreement between the actual and simulated temperatures. Again, the worst agreement comes at the top center of the shield, which is also the area that had the worst agreement using the Labossiere data. Even here though, the general pattern and timing of the simulation to the actual data is very good, with the largest discrepancy coming at the coldest temperatures around 7100 hr, where the difference is about 2.5°C, and 7400 hr, where the difference is about 1.25°C. Again the simulation appears to remain at the phase-change temperature longer than the actual temperatures did from about 6700 hr to 7000 hr. This could be related to moisture variation other than actual or to a time step refinement as explained above in the Labossiere Street data. The agreement at the other locations is excellent, with any errors generally well below 0.5°C.

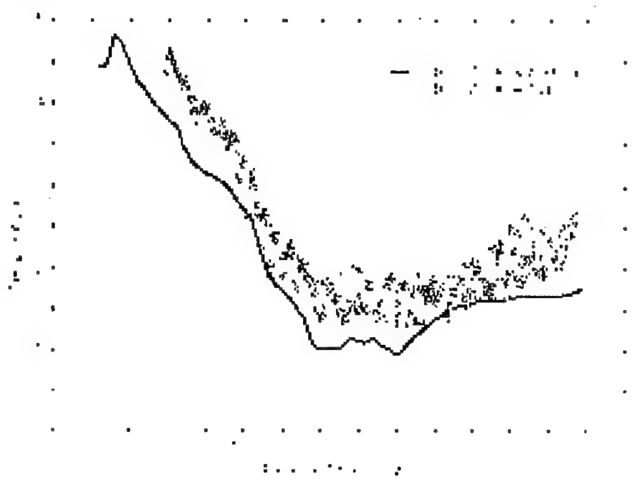
Since the actual physical configuration at Wentworth was different from the design, i.e., ledge did not continue to the surface, numerical simulations were done to determine what the performance of the actual shield would be under the design temperatures. In addition, the actual water temperatures for Wentworth were not known when the design was initially done. Approximate temperatures were used that were obtained by adding a factor to the measured 2nd Avenue temperatures. The time-to-freeze procedure was similar to that described earlier, except



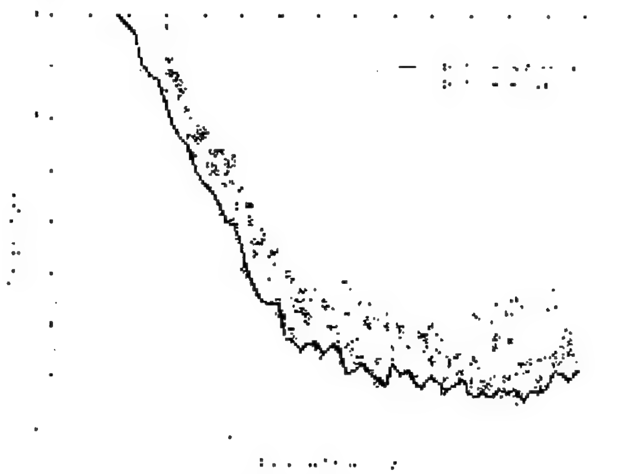
a. *Thermocouple 5 in Figure 8. Top center insulation board, outside shield.*



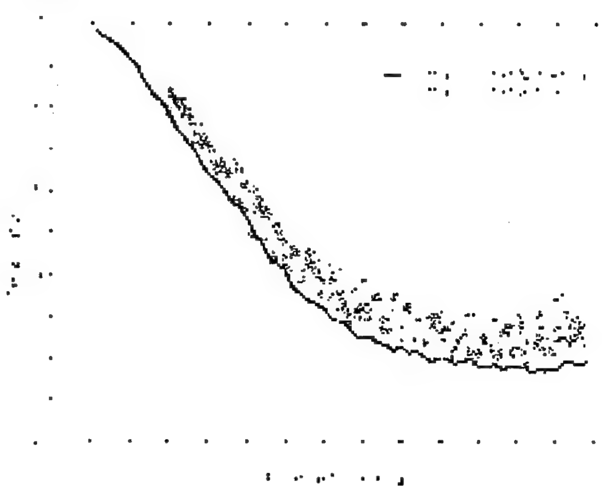
b. *Thermocouple 6 in Figure 8. Top center insulation board, inside shield.*



c. *Thermocouple 12 in Figure 8. Middle of side board, outside shield.*



d. *Thermocouple 8 in Figure 8. Middle of side board, inside shield.*



e. *Thermocouple 11 in Figure 8. Bottom corner, inside shield.*

Figure 16. Actual vs. numerically predicted temperature/time graphs for Wentworth Street during winter 1996–1997.

here the water flow was "stopped" at three times in the simulation: minimum water temperature (MWT), minimum air temperature (MTT) and maximum frost penetration (MFP). At MWT, the pipe never reaches 0°C. The top of the pipe drops to about 0.6°C, and the sides and bottom drop to about 1.2°C, then all slowly rise over the next 200 hr. For both MTT and MFP, the pipe never reaches 0°C, even 200 hr after stopping the water.

To determine what type of protection the shield offered over an unshielded pipe, several numerical simulations were performed using the Wentworth Street physical configuration, without the shield present, and again stopping the water flow at MWT, MTT, and MFP times. At MWT, the pipe top reached 0°C approximately 37 hr after stopping the flow. With a shield, the water temperature never dropped to 0°C. At MTT, the pipe dropped gradually to about 0.4°C compared to staying at about 2° with the shield. At MFP without the shield, the pipe essentially reached 0°C after about 160 hr where it remained for the rest of the 200-hr evaluation time. With the shield, the bottom of the pipe dipped to about 0.25°C approximately 25 hr after the water stopped and then it started to warm up. The above points out the added protection the shield provides under the described conditions.

CONCLUSIONS

The CPAR project demonstrates the viability of burying water lines in the frost penetration zone by designing and installing an insulation shield to protect them from freezing. Using the finite element method to model a buried frost shield appears to give reliable and useful information about the configuration and effectiveness of the shield. The studies show that with the proper boundary conditions and material properties the program predicted temperatures very close to what was measured in-situ. As with all numerical modeling, its accuracy is highly dependent upon the accuracy of the material properties and boundary conditions.

It would be expensive to develop standards to cover every possible combination of climate, soil condition, pipe burial depth, and pipe temperature that could be encountered throughout the frost-susceptible areas of the United States. The finite element procedure described above allows the local designer, who is most familiar with the area of concern, to determine the pertinent variables and assess the effect of each variable upon the proposed design.

The simulation run times used during the verification simulations were 24 to 48 hours, depending upon the time step, length of time modeled, and complexity of the mesh. This was on a '486 66-MHz system with 16 Mb of RAM. There are much faster computers available now and soon to be available that could significantly reduce these times. For example, during the preparation of this report, some of the above scenarios were run on a 233-MHz system with 64 Mb of RAM. On this system a 4-day run on the '486 66-MHz system was reduced to about 6 hr. The smaller scenarios were reduced to 1 hr or less, depending upon their size and complexity.

The boundary conditions required for designing a shield should be conservatively selected to allow for some uncertainty in the exact physical situation present that is being designed for. The designer will need to choose the appropriate boundary conditions (in this case coldest air temperatures on record and recorded water temperatures) and set the failure criteria he is designing around. The failure criterion of the pipe reaching 0°C is probably too conservative in that there is a large amount of latent heat to be used before the water in the pipe will turn to ice, but in these verification runs we had decided to be conservative.

Frost-shielding configuration possibilities can vary depending upon geographical location, extent of pipeline shielded, type of pipe shielded (sewer or water), material characteristics at the site, available room for a shield, and the economics of excavating for different configurations. A shield around a pipe with relatively warm water will allow shallower possibilities and a thinner insulation thickness than one around a pipe with a temperature barely above freezing. A strong point for finite element modeling is the ability to perform several parametric design simulations to assess the effect of any parameter the designer chooses to look at. In addition, the graphical contour output from the modeling can give an extremely useful picture to the designer to assess exactly what impact design changes have on the shield performance. The studies have demonstrated that a shield will provide thermal protection to forestall the freezing of a buried water line under the conditions described for Berlin, N.H.

Something not investigated completely during this study was the use of alternative shield configurations. The inverted-U design worked well in this study because of the limited lateral space available, but other configurations may be more appropriate for different situations.

It was mentioned earlier in the report that con-

Figure 17. Wentworth Street showing clear roadway over insulated pipeline while rest of road has light snow cover.

cern for differential surface icing prevented the Wentworth Street shield from being set closer to the surface. Differential surfacing icing is a possibility during certain meteorological conditions when there is insulation below the surface, because the insulation both retards the natural geothermal heat flux from reaching the surface and retards heat transfer from the soil above the insulation to the soil below it. Under freezing conditions, if moisture is present at the surface, a surface frost may form on the roadway. The width and location of most utility lines means that any surface icing caused by a utility line shield would probably be less than 0.91 m (3 ft) wide and would run along one side of the street. A road may also develop surface icing during certain meteorological conditions even with no insulation present. A study by Sweden's National Road and Traffic Research Institute (VTI) (1981) discusses pavement icing on both insulated and uninsulated roads.

There are also conditions where the roadway over the insulated portion of the shield is bare and the surface over the uninsulated section has a snow or frost covering. Figure 17 shows just such a condition at the Wentworth Street site. The righthand side of the street has the shielded pipe beneath it and is free of snow cover, while the left side still has snow on it. This is probably because the surface is warming and the shield prevents the transmission of that warming energy deeper into the soil, thus causing higher temperatures above the shielded area, melting the surface snow. These conditions could also be enhanced by the different thermal properties between the backfill and the parent material.

The use of a utility line frost shield should be driven by the economics of the situation. Balanced against the extra cost of buying and installing the shield are the decreased excavation costs both for the initial installation and for future maintenance. If it is desirable to use a shield, then the numerical modeling procedure shown here can offer insight into a proper design.

When designing a shield, designers must determine the amount of risk they are comfortable with. The advantage of an FE procedure is the quantifiable output, e.g., time to freeze, that is available as a tool to assess that risk.

RECOMMENDATIONS

The finite element procedure of designing frost shields should be used where designers are confronted with the need to lay water or sewer lines within the frost penetration depth. It can provide very useful, accurate, and quantifiable output to assess various shield designs.

COMMERCIALIZATION/TECHNOLOGY TRANSFER

Owens–Corning Specialty and Foam Products Division (formerly U.C. Industries Inc.) will market the concept of frost-shielding water and sewer lines through its national and international sales focus. It is their intent to use this study as the basis of their product literature. The literature package will be used by the in-house sales staff as an introduction to the concept of frost shielding. Follow-up technical support will be aided by the finite element design methodology developed here.

CRREL will promote the use of frost shielding to the United States Army Corps of Engineers (USACE) and other federal agencies by writing technical reports, conference papers, and other articles as the opportunities arise.

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13. ABSTRACT (*Maximum 200 words*)
Burying utility lines below the maximum frost penetration depth can be expensive when difficult digging conditions are encountered or where existing obstacles make the desired depth expensive to achieve. Protecting the pipeline from freezing by adding an insulation shield would allow a shallow burial option. This can reduce excavation costs or avoid the relocation costs of moving the pipeline to an unobstructed location. A finite-element program was developed to model various subterranean heat-flow situations. It was used to design frost shields for a water line in northern New Hampshire through a 4-year Construction Productivity Advancement Research (CPAR) project with the City of Berlin Water Works, the United States Army Cold Regions Research and Engineering Laboratory (CRREL), and the Owens–Corning Specialty and Foam Products Division as partners. Test sites utilizing shielded pipes were constructed, and simple techniques were explored to expedite the installation of the frost shields. Temperatures at the test sites were recorded both to verify the numerical model and to monitor the shield performance. Overall, the numerical model was capable of very good temperature predictions and provided valuable guidance for the frost shield design.

The industry partner participant in the CPAR project, Owens–Corning Specialty and Foam Products Division, intends to market the concept of frost shielding water and sewer lines to state, city, county, and municipal agen-

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13. ABSTRACT (*cont'd*)

cies responsible for designing and installing such services. This marketing will be supported by design literature, training of in-house engineers and sales personnel, a case study of this CPAR project, and technical support from Owens–Corning.